Advanced High-Temperature, High-Pressure Transport Gasification[1]

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Introduction

The mission of the U.S. Department of Energy's Federal Energy Technology Center (FETC) Office of Power Systems Product Management is to foster the development and deployment of advanced, clean, and affordable fossil-based (coal) power systems. These advanced power systems include the development and demonstration of combustion- or gasification-based advanced power systems, such as pressurized fluid-bed combustion (PFBC) and integrated gasification combined-cycle (IGCC). The goal of these power systems is not simply to provide more efficient power while meeting current New Source Performance Standards (NSPS), but to achieve emission levels one-tenth of the allowable NSPS regulations with respect to particulate, sulfur, and NO_x emissions.

Objectives

The objective of the advanced high-temperature, high-pressure transport gasification program at the Energy & Environmental Research Center (EERC) is to demonstrate acceptable hydrodynamic and gasification performance of the transport reactor demonstration unit (TRDU) gasifier under a variety of operating conditions and using a wide range of fuels. Current objectives are focused on understanding and improving the operation of the transport reactor gasifier itself. A secondary objective of the program is to demonstrate acceptable performance of hot-gas filter elements in a pilot-scale system prior to long-term demonstration tests.

The primary focus of past hot-gas cleanup work on the TRDU located at the EERC was the testing of hot-gas filter elements as a function of particulate collection efficiency, filter pressure differential, filter cleanability, and durability during relatively short-term operation (100–200 hours). A hot-gas filter vessel (HGFV) was used in combination with the TRDU to evaluate the performance of selected hot-gas filter elements under gasification operating conditions. This

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work directly supports the Power Systems Development Facility (PSDF) using the M.W. Kellogg transport reactor located at Wilsonville, Alabama (1) and indirectly the Foster Wheeler advanced pressurized fluid-bed combustor, also located at Wilsonville (2, 3) and the Clean Coal IV Piñon Pine IGCC Power Project.

Approach

This program has a phased approach involving modification and upgrades to the TRDU in order to improve circulation rates to improve gas–solid mixing and increase solid residence time in the mixing zone to increase product gas quality. In the second phase, a change in the loop seal on the TRDU is proposed based on the results from cold-flow modeling tests being conducted at FETC. The third phase would investigate the use of opportunity fuels such as residuum oil supercritical extraction (ROSE) bottoms, biomass, or refuse-derived fuel (RDF).

Project Description

The TRDU is a 200–300-lb/hr (91–136-kg/hr) pressurized circulating fluid-bed gasifier similar to the gasifier being tested at the Wilsonville facility. The TRDU has an exit gas temperature of up to 2000°F (1090°C), a gas flow rate of up to 350 scfm (590 m^3/hr), and an operating pressure of 120 psig (9.3 bar). The TRDU system can be considered in three sections: the coal feed section, the TRDU, and the product recovery section. The TRDU proper, as shown in Figure 1, consists of a riser reactor with an expanded mixing zone at the bottom, a disengager, and a primary cyclone and standpipe. The standpipe is connected to the mixing section of the riser by a J-leg transfer line. All of the components in the system are refractory-lined and designed mechanically for 150 psig (11.4 bar) and an internal temperature of 2000°F (1090°C). Detailed design criteria and a comparison to actual operating conditions on the design coal are given in Table 1. A detailed description of the TRDU and HGFV design has been given in other reports (4, 5).

The HGFV is designed to handle all of the gas flow from the TRDU at its nominal operating conditions. This vessel has a 48-in. (1.22-m) inner diameter and is 185 in. (4.7 m) long with a refractory inside diameter of 28 in. (71 cm) and a shroud diameter of 24 in. (61 cm). The filter design criteria and its average operating conditions are summarized in Table 2. Filter vessel design capabilities include operation at elevated temperatures (to 1750°F [950°C]) and pressures (up to 150 psig [11.4 bar]), with the initial test program operating in the 1000°–1200°F (540°–650°C) range. The HGFV can operate with filter face velocities in the range of 2.5 to 10 ft/min (1.25 to 5.1 cm/s). Up to nineteen 1.5-m candles can be installed in the filter vessel, but 1.0-m candles have been used to date. An existing heat exchanger has been modified to allow for the reduction of the gas stream temperature at the inlet to the filter vessel. An unheated nitrogen backpulse system was constructed to test the effects of backpulsing parameters on candle performance and cleanability. The nitrogen backpulse system was constructed to backpulse up to four sets of four- or five-candle filters in a time-controlled or differential pressure-controlled

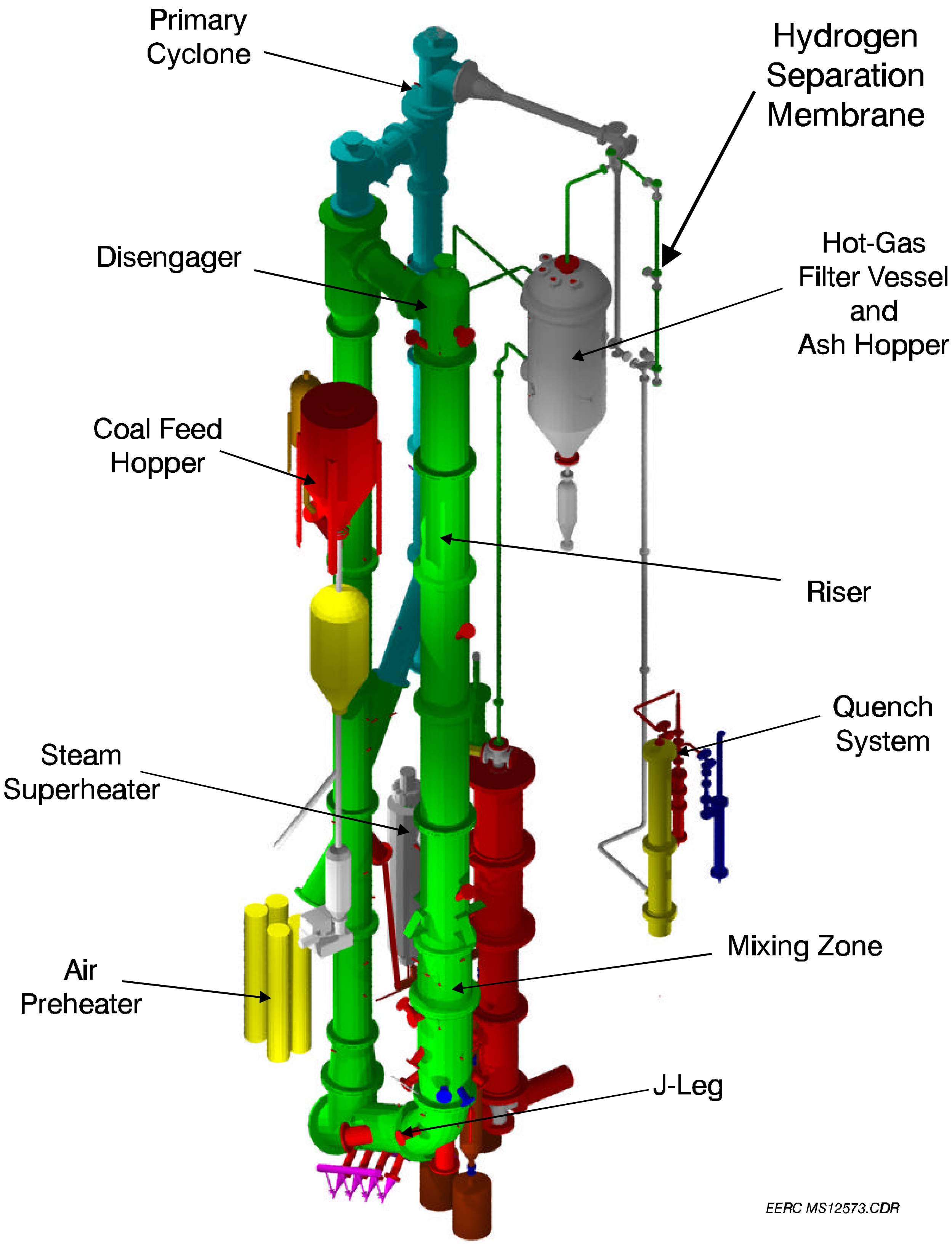

Figure 1. TRDU with HGFV in EERC gasification tower.

TABLE 1

Summary of TRDU Design and Operation on the Same Coal

Parameter	Design	Actual
Coal	Illinois No. 6	Illinois No. 6
Moisture Content, %	5	8.5
Pressure, psig	120	120
Steam/Coal Ratio	0.34	0.39
Air/Coal Ratio	4.0	2.6
Ca/S Ratio, mole	1.5	2.0
Air Inlet Temperature, °C	427	180
Steam Preheat, °C	537	350
Coal Feed Rate, lb/hr	198	232
Gasifier Temperature, maximum °C	1010	950
ΔT, maximum °C	17	100 (60)
Conversion, %	>80	89
HHV[2] of Fuel Gas, Btu/scf	100	113
Heat Loss as Coal Feed, %	19.5	14
Riser Velocity, ft/sec	31.3	25
Heat Loss, Btu/hr	252,000	300,000
Standpipe Superficial Velocity, ft/sec	0.1	0.38

[1] Steady-state conditions were not achieved.
[2] Higher heating value.

sequence. During these tests, the candles were typically pulsed at 35 in. H_2O (87 mbar) above baseline pressure drop across the candles except during the petroleum coke combustion tests, which were pulsed every hour. Sample ports for obtaining particulate and hazardous air pollutant samples were added to the piping system so that a high-pressure and high-temperature sampling system (HPHTSS) can be used to extract dust-laden flue gas isokinetically from the TRDU's reducing environment. Details of the HPHTSS are given elsewhere (5). In the past year, a switch was made from a ceramic tube sheet to a metal tube sheet.

Results

TRDU Fuel Analysis

The fuels tested in the TRDU to date have been a Powder River Basin (PRB) subbituminous coal from the Wyodak seam at the Belle Ayr mine in Gillette, Wyoming; an Illinois No. 6 bituminous

TABLE 2

Design Criteria and Operating Conditions for the Pilot-Scale Hot-Gas Filter Vessel

Operating Conditions	Design	Actual
Inlet Gas Temperature	540°–980°C	510°–570°C
Operating Pressure	8.6–11.4 bar	9.3 bar
Volumetric Gas Flow	350 scfm	280 scfm
Number of Candles	19 (1- or 1.5-m)	13 (1-m)
Candle Spacing	4 in. ℄ to ℄	4 in. ℄ to ℄
Filter Face Velocity	2.5–10 ft/min	4.0 ft/min
Particulate Loading	<10,000 ppm	< 38,000 ppm
Temperature Drop Across HGFV	< 30°C	25°C
Nitrogen Backpulse System Pressure	up to 800 psig	up to 380 psig
Backpulse Valve Open Duration	up to 1-s duration	½-s duration

coal from Seam 6 of the Baldwin mine in Baldwin, Illinois; a western bituminous coal mined from the Hiawatha seam at the SUFCo mine in Salina, Utah; and a petroleum coke from the Hunt Oil refinery in Tuscaloosa, Alabama. Table 3 shows the proximate, ultimate, and x-ray fluorescence (XRF) analysis of all the fuels. All fuels were mixed with Plum Run dolomite from the Greenfield formation before testing in the TRDU. The dolomite was mixed with the respective coals to provide a Ca/S ratio of approximately 2 on a sorbent-only basis for the fuels being gasified (~ 5 wt% for the PRB and SUFCo coals and 17 wt% for the Illinois No. 6 coal) and at a Ca/S ratio of 1.0 for the petroleum coke combustion test.

TRDU Operation

Four test campaigns have been conducted during the past year. During these tests, 179 hours of gasification and 234 hours of coal feed with Wyodak subbituminous coal,
41 hours of gasification on Illinois No. 6 bituminous coal, and 118 hours of gasification on SUFCo bituminous coal were completed. In addition, 70 hours of combustion on a petroleum coke were also completed, with the system gases and fly ash passing through the filter vessel during all of the test campaigns. The TRDU was operated at an average temperature of 1607°F (875°C) for the Wyodak coal tests and up to 1740°F (950°C) for the bituminous coal tests. Coal feed rates ranged from 220 up to 320 lb/hr (100 to 145 kg/hr) depending on the coal type and operating conditions, while the gasifier pressure averaged 120 psig (9.3 bar). The raw moisture-free product gas produced was 6%–10% CO and H_2, 9%–11% CO_2, 1.0%–2.5% CH_4, with the balance being N_2 and other trace constituents. The H_2S concentration averaged 50 to 400 ppm. Correction of the fuel gas concentrations for nitrogen purges and the high system heat loss as a percentage of the coal feed demonstrates that heating values ranging between 105 to 130 Btu/scf can be achieved. See Table 4 for actual operating conditions.

TABLE 3

Wyodak, Illinois No. 6, and SUFCo Coals, Tuscaloosa Pet Coke and Plum Run Dolomite Analyses

	−10-mesh Wyodak Subbituminous Coal	−10-mesh Illinois No. 6 Bituminous Coal	−10-mesh SUFCo Bituminous Coal	−10-mesh Tuscaloosa Petroleum Coke	−35-mesh Plum Run Dolomite
Proximate Analysis, as run, wt%					
Moisture	20.0	8.5	9.5	0.9	NA[1]
Volatile Matter	38.9	36.0	39.1	9.6	
Fixed Carbon	36.4	44.8	43.8	88.5	
Ash	4.7	10.7	7.6	1.0	
Ultimate Analysis, moisture-free, wt%					
Carbon	69.06	69.27	77.10	90.65	NA
Hydrogen	5.19	5.03	4.61	3.89	
Nitrogen	0.84	1.10	1.29	1.70	
Sulfur	0.44	3.55	0.36	5.49	
Oxygen	18.63	9.34	8.29	0.00	
Ash	5.85	11.70	8.40	1.00	
Ash Composition, % as oxides					
Calcium, CaO	26.6	3.2	16.3	11.9	66.6
Magnesium, MgO	7.0	1.6	3.0	5.1	27.5
Sodium, Na_2O	1.3	1.1	4.6	1.0	0.3
Silica, SiO_2	27.8	53.9	38.3	18.9	2.7
Aluminum, Al_2O_3	13.1	21.2	9.3	4.8	1.0
Ferric, Fe_2O_3	5.5	13.6	6.1	7.6	1.3
Titanium, TiO_2	1.3	0.9	0.8	0.0	0.0
Phosphorus, P_2O_5	1.0	0.2	0.2	0.1	0.0
Potassium, K_2O	0.3	1.9	0.2	0.7	0.3
Sulfur, SO_3	16.0	2.5	21.1	13.8	0.4
Vanadium, V_2O_5	ND[2]	ND	ND	30.2	ND
Nickel, NiO	ND	ND	ND	6.0	ND
High Heating Value					
Moisture-Free, Btu/lb	11700	12080	12200	15300	NA
As-received, Btu/lb	9750	11300	11040	15150	NA
Loss on Ignition, as run	NA	NA	NA	NA	43.1

[1] Not applicable.

[2] Not determined.

Factors that affect the TRDU product gas quality appear to be circulation rate, coal type, temperature, and air/coal and steam/coal ratios. A decrease in circulation rate improves the product gas quality by increasing the solid residence time in the gasification zones of the TRDU; however, lower circulation rate tests are more prone to deposition and agglomeration problems as

TABLE 4

TRDU Actual Operating Conditions

Run No:	P056 and P057	P056	P057	P058
Conditions	Gasification	Gasification	Gasification	Combustion
Coal	Wyodak	Illinois No. 6	SUFCo	Pet Coke
Moisture Content, %	20.0	8.5	9.5	0.9
Pressure, bar	9.3	9.3	9.3	8.6
Steam/Coal Ratio (lb/lb coal)	0.29	0.39	0.14 to 0.41	0
Air/Coal Ratio (lb/lb coal)	2.69	2.59	3.34–3.45	15–20
Ca/S Mole Ratio (sorbent only)	2.0	2.0	2.0	1.0
Coal Feed Rate, lb/hr	276.6	232.5	220	50
J-leg Zone, °C, avg.	800	901	866–876	814
Mixing Zone, °C , avg.	850	935	920–950	835
Riser, °C , avg.	840	923	894–914	873
Standpipe, °C , avg.	790	856	828–860	827
Dipleg, °C, avg.	600	576	555–591	471
TRDU Outlet, °C, avg.	795	870	856–877	835
Carbon Conversion, %	89	76	72–87	100
Carbon in Bed, %, standpipe	6 to 15	6 to 15	5 to 20	0
Riser Velocity, ft/s	30	24	25–31	24.5
Standpipe Velocity, ft/s	0.4 to 0.5	.45	0.4–0.45	0.45–0.5
Circulation Rate, lb/hr	3000 to 6000	4000	2650–4200	2000–4000
HHV of Fuel Gas, act., Btu/scf	62 - 75	61	52–75	NA
HHV of Fuel Gas, cor., Btu/scf	105 - 117	113	93–130	
Duration, hr	179	41	118	70
Date	2/17–2/23 3/31–4/3	2/23–2/25	4/3–4/8	5/1–5/4

a result of inadequate gas–solid mixing in the mixing zone. The less reactive bituminous fuels were gasified at higher temperatures to produce a product gas quality similar to those obtained with the Wyodak fuel. Higher operating temperatures increase carbon conversion for the TRDU but again at the risk of increased ash deposition. Higher steam/coal ratios result in improved product gas quality with increased hydrogen and carbon dioxide formation from the water–gas shift reaction, but data also show that additional CO was produced via the steam–carbon reaction. Higher air/coal ratios gave lower product gas quality, especially at ratios above 3.5, with generally under 3.0 providing the best product gas.

The deposits that formed were generally in the mixing zone where the air first enters the TRDU through the burner inlet and comes into contact with the carbon-containing bed material circulating through the J-leg. If the solid–gas mixing is not adequate, localized hot spots can occur. As a result, some of the coal ash can form a sticky layer around bed material particles and start to “glue” impacting particles together in the form of deposits or agglomerates. Conventional bulk chemical analysis provides an analysis of the entire deposit when only the sticky layer on the

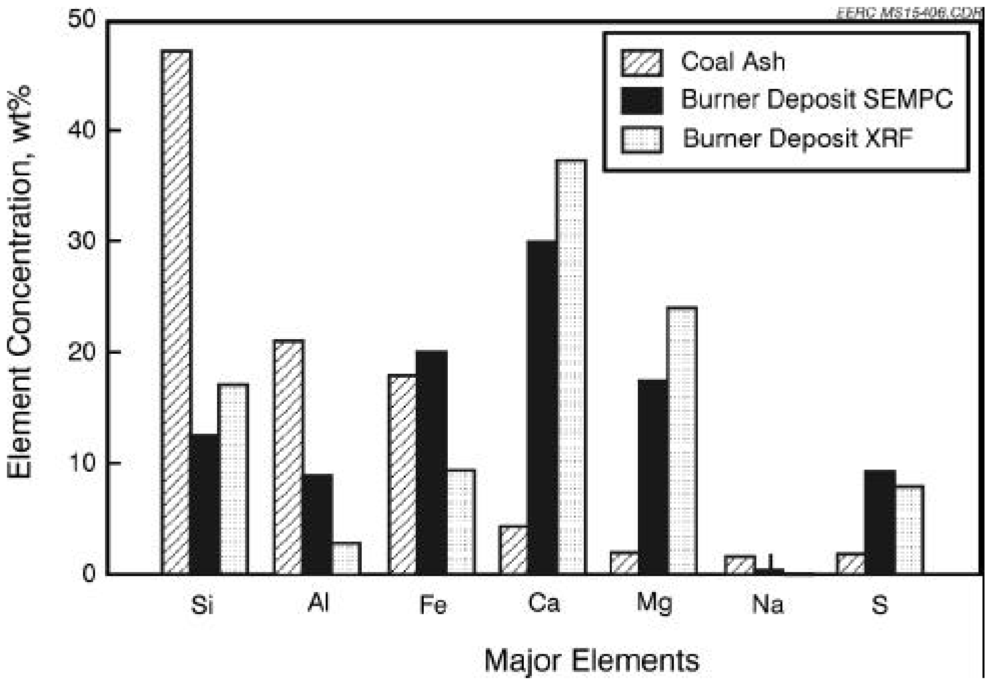

Figure 2. Comparison of Illinois No. 6 deposit analyses.

outer surface bed material particle is of concern. Figure 2 compares a deposit from the Illinois No. 6 coal in the burner region of the TRDU as analyzed by XRF with a manual scanning electron microprobe point count (SEMPC) analysis of only the outer layers found on bed material particles and compares them to the coal ash analysis. As can be seen, the coal ash analysis and the SEMPC analysis are very similar, while the XRF analysis includes a lot of the bed material in the analysis. As shown in Figure 2, the Illinois No. 6 ash deposit is high in iron, calcium, magnesium, and sulfur with the analysis of the necks by SEM showing an enrichment in iron and sulfur over the bulk XRF analysis.

Figure 3 shows a comparison of the SEMPC data for the three different fuels. From this figure, it appears the deposition chemistries of the Wyodak and SUFCo fuels are similar, being primarily calcium–aluminosilicates, with little or no sulfur present in the deposit. The Illinois No. 6 deposit, however, is much higher in iron, magnesium, and sulfur while containing less silica. A comparison of the porosity of the deposits as determined by image analysis on the scanning electron microscope (SEM) shows that the Wyodak and SUFCo coal deposits have a lot more porosity (~52.2%) than the Illinois No. 6 deposit (~24.3%). This indicates that the Illinois No. 6 ash deposit is much harder and more sintered and harder to remove from the system. Circulation rate tests on the SUFCo fuel have shown that deposition at similar operating conditions can be eliminated with the improved solid–gas mixing that occurs at higher circulation rates. The Illinois No. 6 deposits might be eliminated by operation of the TRDU at circulation rates.

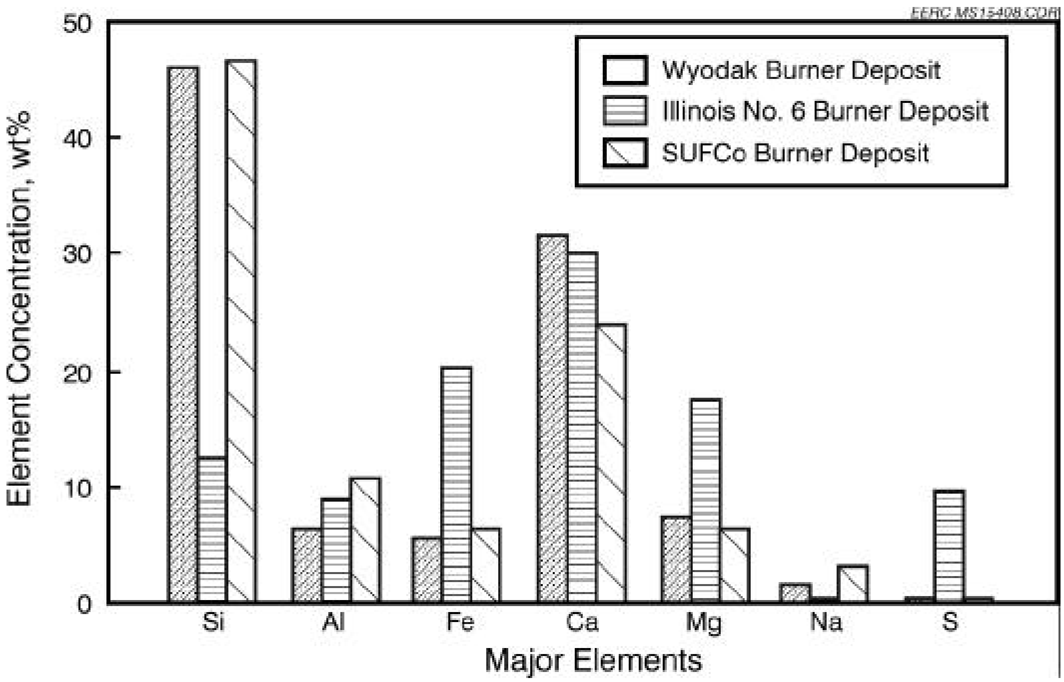

Figure 3. Comparison of SEMPC analyses of burner deposits for various fuels tested in TRDU.

HGFV Operation

Operation of the HGFV during the last year has tested 1-m-long candles from 3M Company (SiC-coated fiber), Schumacher Dia-Schumalith 10-20, and Pall Advanced Separations Vitropore 326 and iron aluminide candles along with Westinghouse fail-safes. There have been no failures of these candles in ~ 700 hours of testing. The HGFV has been operated between 950° and 1050°F (510° and 570°C) at a face velocity of approximately 3.8 to 4.5 ft/min (1.9 to 2.3 cm/s). Backpulse operating parameters were 270 to 400 psig (20 to 28.6 bar) reservoir pressure with a ½-second opening time. The average particulate loading going into the HGFV has ranged from approximately 4500 up to 38,000 ppm with a d_{50} between 7 and 22 μm, depending on the fuel type, quantity of Plum Run dolomite utilized for sulfur control, and whether solids were being recirculated from the dipleg back into the standpipe. A substantial increase in the "cleaned" filter baseline (from ~25 to 90 in. H_2O [60 to 220 mbar]) has been observed in some, but not all, of the tests. This filter ash averaged 40 to 60 wt% carbon and had a low bulk density of approximately 20 lb/ft^3 (0.32 g/cm^3). The small size, the lack of the cohesiveness seen in other filter ashes, and the low density of the ash suggests that a high percentage of the filter cake will be re-entrained back onto the filters after they are backpulsed. Off-line cleaning tests were completed, which indicated that 20 to 25 in. (60 to 62 mbar) of the baseline increase is due to re-entrainment of fine filter ash back on the candles and that off-line cleaning times of up to 300 seconds were needed to allow the backpulsed ash to clear the filters. In gasification mode, the pulse frequency has been short,

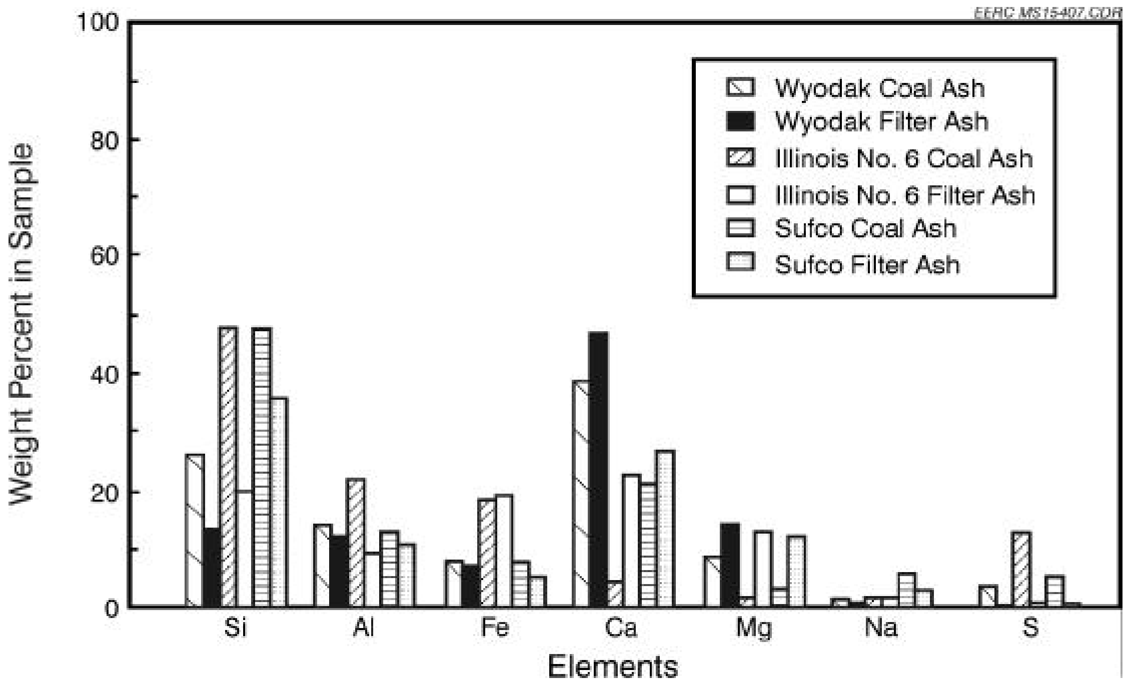

Figure 4. Comparison of HGFV steady-state filter ash samples for various fuels tested in TRDU.

with pulses occurring every 8 to 15 minutes. This rapid pulsing is thought to be due to the high-carbon, low-density filter cake being able to minimize its porosity on the surface of the candle, thereby resulting in a rapid rise in pressure drop across the filters. Injection of filter aid additives has been tested with some success—no additives have increased the backpulsing frequency, but some have reduced or eliminated the rise in baseline pressure drop. The additives that appeared to help reduce baseline pressure drop include a fluid catalytic cracker catalyst support material and combustion coal ash from the Southern Company Services (SCS) PSDF transport reactor (when fed at high rates).

Previous tests have shown that in less than 24 hours after entering gasification, the filter ash is at steady-state coal ash and does not change with increasing operating time (6). Figure 4 compares the filter ash chemistry of the major species from the steady-state filter ash collected from each of the fuels tested. This figure shows that the Illinois No. 6 filter ash is higher in iron and sulfur than either of the low-sulfur Wyodak or SUFCo fuels. The Wyodak fuel is higher in calcium due to the high levels of calcium present in the coal ash. The sodium present in the SUFCo coal ash is divided fairly evenly between the filter ash and the bed material, while the higher silica concentrations for the Illinois No.6 and SUFCo are the result of higher silica levels in the starting fuel.

Applications

This work directly supports the PSDF utilizing the M.W. Kellogg transport reactor located at the SCS Wilsonville, Alabama, site and indirectly the Clean Coal IV Piñon Pine IGCC Power Project located at the Sierra Pacific Power Company's Tracy Station near Reno, Nevada.

In addition to direct support for the PSDF at Wilsonville, TRDU operation and filter element testing have benefitted other ongoing projects at the EERC. The first sampling and analysis activities were conducted to generate hazardous air pollutant data concerning trace metal transformations, speciation of mercury, and metal concentrations at selected points within the TRDU and hot-gas cleanup in support of a project entitled "Trace Element Emissions" funded by FETC, Morgantown. In addition, materials and ash data concerning the high-temperature filter media and ash interactions were collected and analyzed in support of a project entitled "Hot-Gas Filter Ash Characterization" jointly funded by FETC Morgantown and Electric Power Research Institute (EPRI). The exposure of various ceramic and metallic specimens to a reducing environment continues to be a side benefit to this program. Filter and ash samples have been colleted, and shipped to Southern Research Institute and Oak Ridge National Laboratory for analysis.

Future Activities

Future plans are to modify the transport reactor mixing zone and J-leg loop seal to increase solids circulation and backmixing, thereby increasing solids residence time and gasifier performance. Enriched air/oxygen-blown gasification tests will also be conducted. The effects of different fuel types on gasifier performance and the operation of the hot-gas filter system will be measured.

Acknowledgments

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